IEA/H2/T11/FR1-2000

INTERNATIONAL ENERGY AGENCY
HYDROGEN IMPLEMENTING AGREEMENT
TASK 11: INTEGRATED SYSTEMS

Final report of Subtask A:
Case Studies of
Integrated Hydrogen Energy Systems

Chapter 5 of 11

T. Schucan
Paul Scherrer Institute
Switzerland

Chapter 5
SCHATZ SOLAR HYDROGEN PROJECT

1. PROJECT GOALS

The Schatz Solar Hydrogen Project began in the fall of 1989. It is a stand-alone photovoltaic energy system that uses hydrogen as the storage medium and a fuel cell as the regeneration technology. Its goal is to demonstrate that hydrogen is a practical storage medium for solar energy and that solar hydrogen is a reliable and abundant energy source for our society.

A schematic for the system is shown in Figure 5.1. It is installed at the Humboldt State University Telonicher Marine Laboratory (124.15°W, 41.06°N) and the Lab's air compressor system, used to aerate aquaria, is the load. When PV power is available, it is used directly to supply the load. Any excess power is supplied to the electrolyzer to produce hydrogen gas. When the array cannot provide electricity, the stored hydrogen serves as fuel for the fuel cell, providing uninterrupted power. If the storage is depleted, the system returns to utility power supplied by the grid.

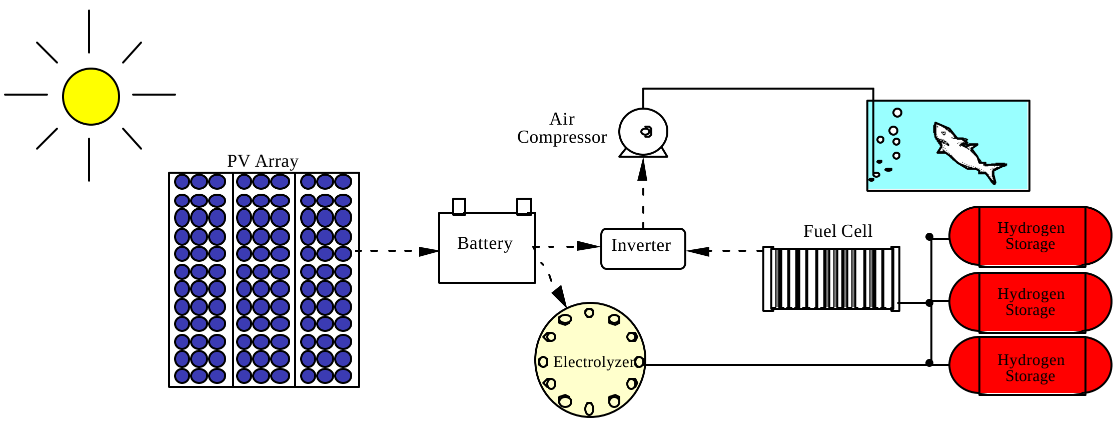

Figure 5.1: System Schematic

The objectives of the Schatz Project are:

- to assess the storage efficiency of hydrogen when used as a medium to store solar electricity
- to assess the use of a proton exchange membrane fuel cell as a means of regenerating electricity from stored hydrogen and oxygen
- to design, test, and utilize a computer based control system which will allow for efficient component integration and provide for reliable, unattended operation
- to monitor operating and environmental parameters to chronicle system performance and to allow development of a simulation model

2. GENERAL DESCRIPTION OF PROJECT

The impetus for this project came in the form of an intriguing offer from Mr. L. W. Schatz, the former president of General Plastics in Tacoma Washington. Mr. Schatz was, and still is, very interested in furthering the use of non-polluting hydrogen technology. He approached Dr. Peter Lehman in the spring of 1989 and proposed the arrangement that continues to this day wherein the Humboldt State University Engineering Department faculty and students formed the Schatz Energy Research Center (SERC). SERC's first project was to design, construct, and maintain the facility in Trinidad, California, USA. SERC has since grown into a research laboratory that employs 17 engineers, physicists, and students.

Design work began in the fall of 1989 and the PV array was installed in the summer of 1990. The building was contracted out to the McKinleyville High School Industrial Arts Class where it was designed and assembled before being installed on the site in Trinidad in the fall of 1990. The electrolyzer was installed shortly thereafter. A PEM fuel cell was obtained from Ergenics Power Systems in 1991 but a variety of problems prevented this unit from providing reliable power. Unfortunately, the company went out of business before a replacement unit could be obtained. This incident, coupled with a lack of available, affordable fuel cells induced us to manufacture our own stack.

In the fall of 1992, The Schatz Fuel Cell Laboratory was formed and began a collaborative effort with Texas A&M University to design and construct a 1.5 kW PEM cell using air as the oxidant. In December of 1994 the completed unit was installed in Trinidad. An overview of the plant is shown in Picture 5.1.

Picture 5.1: A fifth grade class visiting the Schatz Solar Hydrogen Project for an educational field trip

3. DESCRIPTION OF COMPONENTS

3.1 PV Array

The PV array consists of 192 Arco M75 modules configured into 12 independent sub-arrays. Each sub-array consists of 16 modules, wired in 8 series pairs for 24 V_{DC} operation. The sub-arrays are electrically isolated from each other by 60 A Schottky diodes. The sub-arrays are individually switchable to either the load or the electrolyzer. If not needed, the sub-arrays can be shorted; this also serves as the “safety off” configuration. The nominal power rating for the array is 9.2 kW.

3.2 Battery

The power supplied by this system must be consistent and reliable for the air compressor to function properly. Because PV modules depend entirely upon the vagaries of the weather, their output can vary substantially from second to second. For this reason we have included a small battery in the system to function as a buffer between the PV array and the inverter. This way, the battery can absorb or supplement momentary excesses or deficiencies of power from the array. This greatly reduces the need for frequent switching in and out of individual sub-arrays by the control system.

Initially, the system contained a 37 Ah nickel-cadmium (NiCd) battery. Unfortunately, this battery failed early on and had to be replaced. At this time our battery consists of four Exide GC-4, 6V, 220 Ah deep cycle golf cart batteries.

3.3 Electrolyzer

The electrolyzer is a medium pressure, bipolar, alkaline unit manufactured by Teledyne Brown Engineering. It consists of a 12 cell electrolysis module designed to deliver 20 standard liters per minute (slm) of H_2 gas at a current of 240 A at 24 V_{DC}. The module contains an electrolyte of 25% (by weight) potassium hydroxide.

It was chosen because it is the only commercial electrolyzer available in the correct size (7.2 kW maximum, 6.0 kW nominal) which supplies pressurized hydrogen, thus eliminating the need for supplementary compression.

3.4 Storage

The H_2 gas exits at 790 kPa and is stored in three steel tanks with a total capacity of 5.7 m^3. This provides approximately 133 kWh of storage at the higher heating value (HHV) for H_2 which will operate the load (600 W) for approximately 110 hours assuming a practical fuel cell efficiency of 50% (HHV). Three small tanks were selected as opposed to one large one due to local fire codes. Tanks larger than 500 gallons are subject to much more stringent set-backs from occupied structures.

3.5 Fuel Cell

A proton exchange membrane (PEM) fuel cell was chosen because of its passive operation, its high efficiency, and its ability to provide power quickly from a standby configuration. While the initial stack from Ergenics required pure oxygen at 250 kPa, the unit which we eventually developed utilizes low pressure (20 – 35 kPa) air as the oxidant. This eliminates the attendant problems and dangers associated with the use of pure oxygen.

The unit consists of 48 cells in series, each of which has an active area of 150 cm^2, for a peak output of 1500 W. The membrane and electrode assemblies (MEA's) consist of DuPont Nafion™ 115 as the membrane and E-TEK solid polymer electrolyte electrodes with 1 mg/cm^2 platinum loading.

3.6 Inverter

We are using a Trace DR1524 inverter to convert our 24 V_{DC} (nominal) power to the 110 V_{AC} that the compressor requires to operate. This unit was selected due to Trace's reputation for reliability.

4. INTEGRATION OF COMPONENTS

4.1 Matching the PV Array and Electrolyzer

Various choices are possible in coupling the PV array and the electrolyzer. Significant work has been reported by the HYSOLAR project on the enhancement in performance that is achievable by tracking the maximum power point and then using DC to DC voltage conversion to match the electrolyzer voltage. Though enhancement is possible, its small magnitude plus the extra complexity and cost led us to choose direct coupling for our system.

Since the array and electrolyzer are directly coupled, it is crucial that there be a good match between the electrolyzer's operating points and the array's maximum power points. These will vary as conditions change but, in any circumstance, the electrolyzer must not be allowed to operate at a voltage much higher than the voltage at maximum power, V_{mp}. The steep decline in power beyond V_{mp} would be a serious loss.

The operating characteristics of the Altus 20 are temperature sensitive as can be readily seen from the various current-voltage (IV) curves shown in Figure 5.2.

According to Teledyne, the operating voltage of the module is expected to increase by 3.3 V over an operating life of approximately 25,000 hours. Additionally, as the temperature of PV modules increases, voltage output decreases. These, then, are the two main criteria for matching the array to the electrolyzer module.

The match between the array and electrolyzer can be shown by superimposing the possible range of electrolyzer operating voltages on the sub-array power curves. This is shown in Figure 5.3.

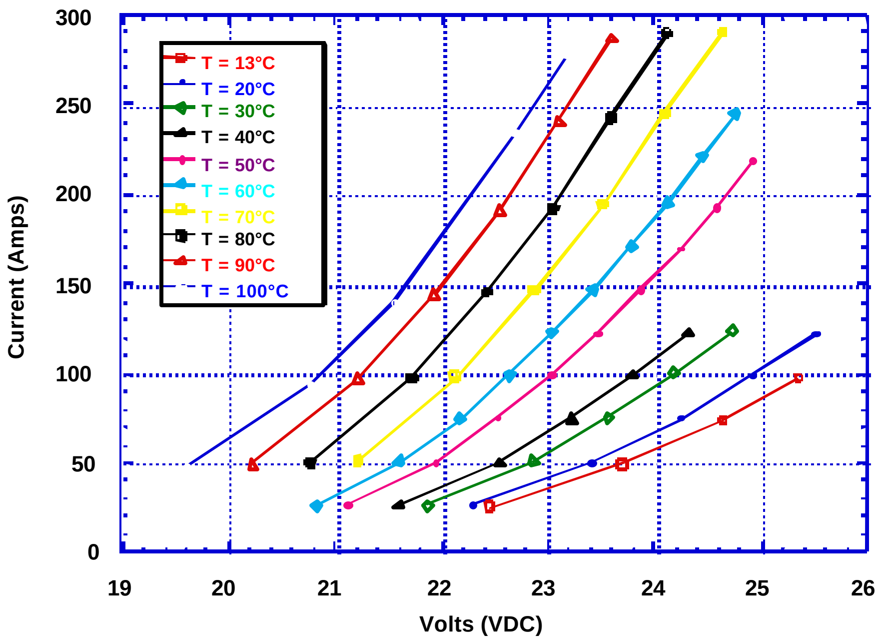

Figure 5.2: Electrolyzer I-V curves at varying temperatures

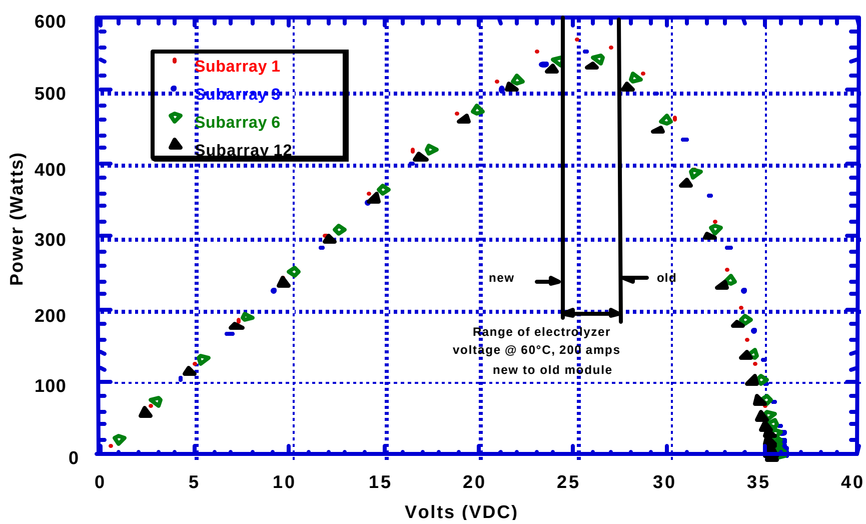

Figure 5.3: Sub-array power curves and electrolyzer operating range

At nominal operating conditions, the array and electrolyzer match very well. The worst of circumstances will occur with an old, cold electrolyzer and a warm array. Because of the cool, maritime climate, the array will never get much hotter than the 47°C. Even under these circumstances, the operating voltage would not exceed 29 V_{DC}. This would result in a power loss of approximately 10%, which would not be a serious loss.

4.2 System Control

The control system is designed to implement the basic logic and to do so automatically. In addition to regular operation, the system monitors various safety interlocks and provides for a shutdown if need arises. The system is configured so that input sensors can be calibrated and software parameters can be varied via on-screen commands to the control computer. Any or all of the subsystems can be run independently, with manual or automatic control, and a continuous graphic display provides constant updates on system configuration and operating parameters.

4.3 Control Hardware

A Macintosh SE microcomputer (SE) is used for the control system. The SE receives input parameters (both analog and digital) from a MacADIOS II SE data acquisition system via Analog Devices backplanes and Opto-22 digital backplanes.

Currents are measured with shunts, voltages directly, and temperature with a type T thermocouple, each with appropriate signal conditioning and amplification. The digital inputs are delivered to appropriate digital modules that provide a 0 or 5 V off-or-on signal.

The SE controls system operation by individually switching relays and solenoids. Output signals are sent by the computer through additional Opto-22 digital backplanes. 120 V_{AC} power for the coils of relays and solenoids is provided by optically isolated switching modules.

4.4 Control Algorithm

In the daytime the control algorithm, which allocates sub-arrays to the load or the electrolyzer, begins by determining the sub-array input currents and system configuration. A charging flag indicates whether the battery has been most recently charged or discharged. When the charging flag is on (recently discharged), the program determines the minimum number of sub-arrays which, when switched to the load, will provide enough PV current to exceed the current drawn by the inverter. It switches these to the load and excess current charges the battery. All other sub-arrays are connected to the electrolyzer.

When the charging flag is off, the program allocates the maximum number of sub-arrays which will not cause the PV current to exceed the inverter current. The deficit is provided by the battery. All other sub-arrays are again connected to the electrolyzer.

There are three circumstances that cause the program to limit the current to the electrolyzer and allocate fewer sub-arrays than are possible above. These are: 1) the electrolyzer can accept a maximum current of 275 A under any circumstances; 2) at low currents, the H_2 impurity in the O_2 line is too large so the program prevents operation below 20 A; and 3) at low temperatures, the electrolyzer can accept less than the maximum current. At 30°C and below, currents up to 125 A are allowable. At 60°C and above, a maximum current of 275 A is allowable. Between these two temperatures, the current limit increases linearly.

At night, or when there is insufficient insolation to provide PV power to the load, the control system starts up the fuel cell and, when its output stabilizes, transfers this power to the load. When the sun comes up, or the level of insolation increases sufficiently, the load is transferred back to the PV array.

4.5 Safety Interlocks

The system has several safety interlocks. The electrolyzer has its own programmable controller that monitors operation. If any of the monitored parameters is out of normal range, a signal is produced which, under normal circumstances, would shut down the electrolyzer's DC power supply. The SE monitors that signal and shuts down if it is activated. Power to the feedwater pump is also monitored. This serves as a safety backup to the feedwater level sensor. If the sensor fails in the full position, neither the pump nor a shutdown would be activated. This would cause loss of electrolyte water and electrolyzer module failure. If AC current does not flow to the pump after 50 Ah of operation (as it should), a safety shutdown is effected.

The electrolyzer is mounted within a sealed, ventilated hood. Bacharach combustible gas alarms are mounted in the laboratory room and inside the hood. If either indicates an alarm condition (set at 40% of the lower explosive limit), the system shuts down. The hood is also fitted with an air movement sensor. If ventilation in the hood fails, a shutdown occurs.

While the control computer is connected to an uninterruptable power supply (UPS) this unit is intended only to provide sufficient back-up power to safely shut down the system in the event that the local utility grid fails.

A fail-safe power transfer system has been incorporated to return the load to the local power grid in the event that the solar hydrogen system cannot supply power. This allows the system to run automatically and ensures that the air compressor will run at all times without the need for human intervention. The marine laboratory has always had an auxiliary generator system in place.

The control system microcomputer and the monitoring system microcomputer also exchange signals to show they are operating properly. If either computer fails or detects an abnormal condition, a shutdown occurs. This protects against the possibility that the control system SE would crash and leave the system in a dangerous configuration.

Finally, if the smoke detector or the emergency push button shows a positive signal, a shutdown also occurs.

5. OPERATIONAL EXPERIENCE AND PERFORMANCE

5.1 1995 Operating Data

The system first went on line late in 1992. At that time, the PV array and the electrolyzer were fully functional and the data collection system began operating. From that time through the end of July 1998, the system has been on line for 26010 hours, has powered the load for 7012 hours, and produced 4556 normal cubic meters (Nm^3) of hydrogen gas. Over this period, the electrolyzer has had a Faraday efficiency of 96.4%, an electrolyzer efficiency of 79.2%, and a voltage efficiency of 84.0%.

Our most complete set of operations data is from 1995. Over the course of this year, the system was operational for a total of 6326 hours, the load was powered by the PV array for 2272 hours, the fuel cell for 1490 hours, and the local utility for 2538 hours. During 1995, 208244 Ah of electricity were provided to the electrolyzer, which in turn generated 1096 Nm^3 of hydrogen gas.

A bar graph showing the daily sources of power to the load over the course of the year is shown in Figure 5.4.

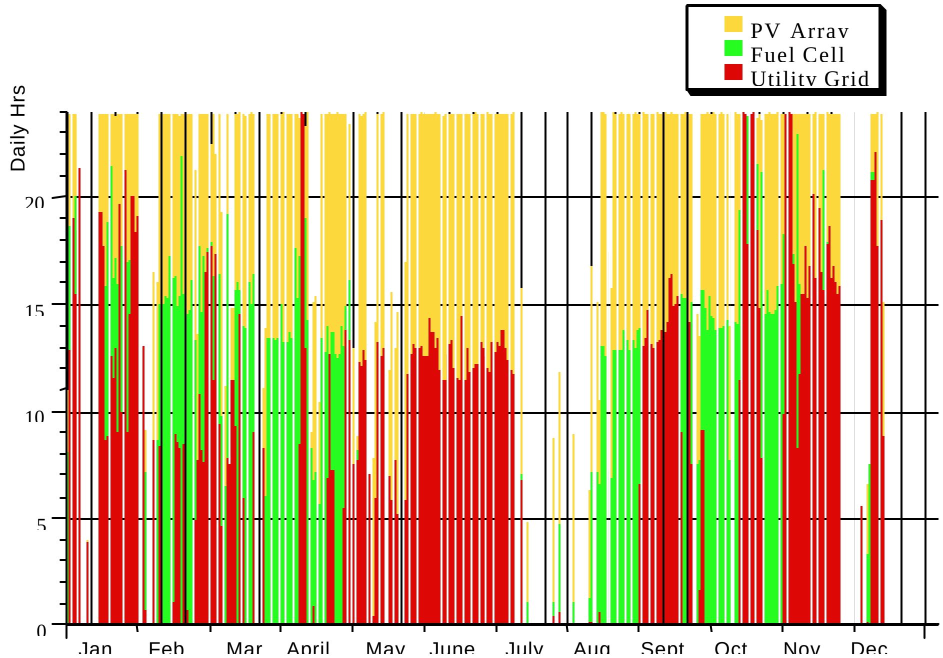

Figure 5.4: Daily totals of the source of power supplied to the load in 1995

As can be seen from Figure 5.4, there are large blocks of time in which the load is powered entirely by the PV array and the fuel cell. Areas where fuel cell operation are not represented are generally due to control software modification and debugging, or, as in the case of the period from May through July, a result of stack modification and damaged cell replacement.

5.2 Efficiency Definitions

The following definitions are used for the efficiency calculations:

Electrolyzer $\dfrac{\text{Hydrogen produced in watts}}{\text{DC power supplied to the electrolysis module}}$

Faraday $\dfrac{\text{Actual amount of hydrogen produced}}{\text{Theoretical production of hydrogen for the current that passed}}$

PV $\dfrac{\text{PV power used by the system}}{\text{Solar power incident on the array}}$

System $\dfrac{\text{Hydrogen produced in watts + DC power to the load}}{\text{Solar power incident on the array}}$

Voltage $\frac{\text{Theoretical voltage required for hydrogen production}}{\text{Actual voltage necessary for hydrogen production}}$

Fuel Cell $\frac{\text{Power supplied by fuel cell in Watts}}{\text{Hydrogen consumed by fuel cell in Watts}}$

There are a few noteworthy comments to make about these definitions. For the electrolyzer efficiency, the DC power supplied to the electrolysis module refers only to the power used for electrolysis; it does not include the auxiliary power requirements necessary for operating the electrolyzer, such as the control system, feedwater pump, and cooling system.

The area of the entire photovoltaic array (made of 12 sub-arrays) is used for the PV and system efficiencies. The photovoltaic system, load and electrolyzer have been carefully matched to maximize power production, efficiency, and utilization. However, under certain circumstances one or more sub-arrays is sometimes disabled from the system because the power output is either too low or too high for operating the load or electrolyzer. When these conditions occur, the PV and system efficiencies are depressed because part of the available solar power is not being utilized by the system (i.e., the value of the denominator increases while the numerator remains constant or decreases).

The second term of the system efficiency equation, "DC power to the load" refers to the photovoltaic array power delivered to the load and buffer battery in this circuit. However, when the load draws upon the buffer battery for extra power, this term refers only to the photovoltaic power being supplied to the load; it does not include the battery power, since this would be double counting the array power that was delivered to the battery during the charging period.

5.3 Efficiencies

Efficiencies were calculated according to the definitions presented above. These overall averages, as shown in Table 5.1, are based upon data that were averaged over short intervals (typically 2-3 minutes) before being recorded.

Table 5.1: Average Efficiencies for 1995 (%)

Faraday	Electrolyzer	Voltage	PV	System	Fuel Cell
97.6	80.1	83.5	6.7	5.7	43.1

As can be seen from Table 5.1, the various efficiencies related to the electrolyzer are all quite good. The PV and System efficiencies, on the other hand, are somewhat less than expected. Direct testing of individual sub-arrays at solar noon found efficiencies approaching 10%. Prior to the implementation of fully automatic operation, the average PV efficiency was in excess of 8%. Clearly there is some dynamic at work here that is driving the efficiency down.

Unfortunately, we have not been able to develop a method for determining the number of sub-arrays actually providing power to the system at any given time. As a result these particular efficiencies are calculated using the entire area of the PV array by default. As mentioned above, this can have a substantial effect upon the final value.

There are several sets of circumstances in which one or more sub-arrays cannot be utilized. For instance, during start-up periods when the electrolyzer is not yet up to operating temperature it can only run at half power. In addition, during periods of low insolation (which occur frequently in this coastal region), there is more power available than is required to run the load, yet not enough to provide the minimum 20 A to the electrolyzer that is necessary to prevent dangerous levels of hydrogen contamination in the oxygen stream. In this case, the power cannot be utilized. Lastly, we have observed periods of intense cloud focused sunlight when each individual sub-array is capable of producing in excess of 30 A of current, yet one or more must remain idle as the total power would considerably exceed the system's ability to absorb it.

Lastly, during the summer there were periods when the fuel cell could not use the hydrogen stored in the tanks at night as fast as the electrolyzer was producing it during the day. As a result, there were many occasions when the tanks would be full by midday and the electrolyzer would be forced to go into 'standby mode' in spite of an abundance of sunlight. This situation would leave eleven sub-arrays idle with the twelfth powering the load. For instance, on August 19, 1995 the PV grid ran the load for 11.06 hours, but the electrolyzer ran for only 5.35 hours. The resulting PV efficiency was only 5.0%.

As a result of all of these circumstances, there are significant periods of time in which all of the measured solar energy cannot be used, yet that total is used in calculating the PV and System efficiencies.

Prior to fully automatic operations we ran the system only when an operator was present. Typically this would have been during normal working hours. During this extended period we measured PV and System efficiencies that were, on average, more than 1 percentage point higher. The subsequent decrease in these efficiencies following the switch to automatic operation can be attributed to the much broader range of operating conditions that the system encountered due to 24-hour operation. A larger pool of data with a much higher percentage of marginal operating conditions, such as those that are found at sunrise and sunset, provide a more appropriate picture of 'real world' operations, as opposed to the previous data which was comprised largely of middle of the day measurements.

5.4 Electrical Storage Efficiency

One of our primary objectives with this project was to assess the efficiency of hydrogen for storing electrical energy from the sun. For purposes of this analysis, we considered this to be the electrical energy produced by the fuel cell divided by the electrical energy used by the electrolyzer to produce the same quantity of hydrogen.

To perform this calculation we took several blocks of time in which the entire system ran continuously for several days at a time during 1995. Over this 45-day accumulation of data, we measured the cumulative quantities of hydrogen gas and electrical energy produced and consumed by the system. As it turns out, the electrolyzer requires, on average, 4.17 Wh to produce a single standard liter of hydrogen, while the fuel cell produces an average of 1.42 Wh from one liter. The average electrical storage efficiency of this system is therefore 34%. This is slightly lower than we had hoped for, but typical of what can be expected for this storage cycle. Furthermore, the fuel cell did not perform as well as we had expected.

5.5 Shutdowns

As can be seen in Figure 5.4, there are quite a few periods of time in which the system was not operational. The total on-line period of 6,326 h accounts for 72% of a year, leaving the remaining 28% as non-operational.

This system is designed to function automatically with only the occasional need for an operator. In general, this works quite well with the control system routinely performing its tasks. However, when there is an emergency shutdown, for whatever reason, the system cannot be restarted without an operator. As a result, a fairly innocuous cause, such as a brief loss of utility grid power to the ancillary equipment, can result in a multi-day shutdown if an operator is unavailable to restart the system. Unfortunately, due to our location in a fairly remote coastal region, power outages and sags are not uncommon. Table 5.2 gives a complete listing of all the emergency shutdowns that occurred in 1995.

Table 5.2: 1995 Shutdowns

Cause	Frequency
Hood exhaust fan sensor	5
Utility power outage	4
Monitoring computer not responding	3
Low electrolyzer current	3
Computer failure	2
Electrolyzer feedwater conductivity too high	2
Electrolyzer temperature too high	1

Some of the shutdowns, such as the hood exhaust fan error, occurred repeatedly until the source of the problem (a defective switch) was determined and corrected. The high electrolyzer temperature was caused by an inadvertently disconnected thermocouple.

Other shutdowns were the result of computer and software idiosyncrasies. For instance, the '*monitoring computer not responding*' error is the result of writing data files to a crowded folder on the hard drive. The bookkeeping necessary to create a new file in the presence of a large number of old files would delay the monitoring computer sufficiently, so that it could not respond in a timely fashion to the control computer's routine inquiries. Additionally, if the control computer happened to turn off the electrolyzer while the monitoring computer was measuring electrolyzer current, a transient reading would cause an erroneous shutdown for '*low electrolyzer current*'. Both of these problems were solved, the former by having the operator sort the data into monthly folders, and the later by requiring two consecutive readings for a shutdown to occur. Finally, the computer failures seemed to be related to transient problems with their power supplies, as nothing obvious was found, and they went away of their own accord.

5.6 Maintenance

In addition to unscheduled shutdowns, there were several occasions that required the system to be shut down for the installation or maintenance of equipment. The electrolyzer requires fairly extensive inspection and maintenance twice a year. This typically requires one to two days, depending upon what is found during the inspection. Other maintenance includes changing the deionization filters for the electrolyzer feedwater, testing the various safety interlocks, regenerating the desiccant in the Employ pyrometer, testing and recalibrating the various sensors, checking and topping off the electrolyte in the battery bank, and testing all the safety interlocks.

5.7 Equipment Failures

5.7.1 Battery

In late December 1993, we began experiencing occasional system shutdowns due to low battery voltages during overnight standby mode. These events tended to occur following periods of extremely low insolation and our initial thought was that the 20 cell, 37 Ah nickel-cadmium (NiCd) battery was simply not being charged sufficiently. However, continued problems led us to run discharge tests that revealed that its capacity had diminished to less than 10 Ah.

NiCd batteries are known for their ability to sustain thousands of deep discharge cycles without damage. Although this battery had been in place for nearly three years, the system was in full time operation for only five months at the time of the failure. We concluded from this that the manner in which the battery was being used rather than the length of service was the culprit.

For this system it is not unusual for charging current to approach 20 A on sunny days (the output of a single sub-array). This amounts to a C2 charge rate, wherein the battery is charged at a rate that would, if continued for an hour, equal one half its total capacity. The manufacturer recommended that this battery be charged at a C5 rate.

With all of this in mind we decided to replace the failed battery with a larger capacity unit in order to decrease the rate of charge. As the cost of a large NiCd unit was prohibitive, we obtained an Exide Commercial lead-acid battery. Although lead-acid batteries should not be discharged below 80% of their rated capacity, the substantial increase in absolute capacity more than compensates. At a 20% depth of discharge, the usable capacity of the lead-acid battery is 44 Ah. Further, the charge rate problem experienced with the NiCd is no longer an issue as a 20 A charging current is equivalent to a C11 charge rate.

We identified a further problem with the battery system. Any time that the system was shut down, the inverter would remain connected to the battery. Although this unit goes into a reduced power ‘standby mode’, it nevertheless draws about 0.5 A. This adds up to 12 Ah/day, a quantity sufficient to discharge the battery to dangerous levels if the system remains down for several days. We corrected this oversight by adding a relay to the control system to disconnect the battery from the inverter during shutdowns.

5.7.2 Fuel Cell

In May of 1995, after the fuel cell stack had been in operation for approximately 5 months, several individual cells showed signs of serious degradation, making it difficult for the unit to start up properly. The stack was removed from the system and disassembled. Serious corrosion was discovered internally in several regions of the threaded stainless steel rods which held the stack together. This corrosion had contaminated several of the cells, and was the likely cause of poor cell performance. The stainless steel rods were replaced with nylon rods and new MEAs were manufactured and installed. The stack was reinstalled on July 7, 1995.

In November 1995, we saw the first signs of a cross leak in one of the cells in the rebuilt fuel cell stack. Initially, the only real problem was in starting up the stack when cold. However, following a period of prolonged shutdown (6 weeks) due to the holidays, as well as a failure of the fuel cell control computer, performance declined precipitously. We speculate that this long period of non-operation allowed the Nafion membranes to dry out, turning a small perforation into a substantial tear. By February 20, 1996, the stack could no longer be started due to low cell voltage. As we were concerned that further attempts to operate the stack might result in dangerous mixing of hydrogen and air, we decided to remove this stack from further service pending future repairs. Since that time, our fuel cell efforts have largely been diverted into electric vehicle research, so this stack remains off-line.

5.7.3 HydroNet system

Prior to July 3, 1996, environmental data were collected from the PV array area via a HydroNet field data collection system. When this system failed, we discovered that parts are no longer available. A Dataforth SCM9B system with new thermistors was selected and obtained, but we were unable to install this equipment until June 1998. During the intervening period of time, the data on wind speed, insolation, air temperature, and PV module temperatures were not collected.

6. DATA ACQUISITION

A variety of data is measured and recorded whenever the system is running. These include the following:

- Temperature — Electrolyzer (various locations)
Ambient air in the array field
PV modules (3)
Hydrogen storage tank
- Pressure — Hydrogen at the electrolyzer
Hydrogen storage tank
- Gas Flow — Hydrogen from the electrolyzer
Hydrogen to the fuel cell
- Voltage — Electrolyzer
Battery
Inverter
- Current — Electrolyzer
Battery
Inverter
- Miscellaneous — Wind speed
Insolation

Most of these data are available on diskette in tabular form for any period in which the system was running. Note that, at times, various components of the system have been off-line and are not included in these files.

In addition to the daily operational data we also have data available for certain of the system components. For example, we have individual IV curves for each of the 192 PV panels in the array, as well as for the twelve sub-arrays. Electrolyzer data include the IV curves taken at various operating temperatures, as well as a range of steady state constant power runs using a DC power supply. Finally, we also have IV curves for the fuel cell prior to its demise.

7. SIMULATION

7.1 Hydrogen Production

Several mathematical models have been developed by SERC staff members to simulate the performance of the photovoltaic array and the electrolyzer in the system. These models were developed using a variety of computer software tools such as Language Systems FORTRAN for programming, Minitab for statistical analysis, and Kaleidagraph for graphing and statistical analysis.

We used these models to simulate our system and then made direct comparisons to measured performance over an eight-day period with highly variable weather. We ran the simulation for this period with a number of variations in order to compare different simulation configurations. The variations include running the simulation with two different electrolyzer temperature models: the Vanhanen Electrolyzer Temperature Model and the Jacobson Electrolyzer Temperature Model. We also made runs with each day broken into time intervals of different lengths: once with one-hour time intervals and once with three-minute time intervals. Finally, we ran the simulation once using the measured electrolyzer environmental temperature from a data file and another time setting this value equal to a constant 20°C. The hydrogen production results from these runs for the eight day period are presented in Table 5.3.

The results given in Table 5.3 show that the simulation's predicted values and the measured values are in close agreement for all of the different configurations. This is important in part because it establishes that the simulation does an excellent job of predicting hydrogen production and in part because it shows that the different configurations have almost no effect on the simulation performance.

The Jacobson electrolyzer temperature model is slightly better at predicting the electrolyzer temperature than the Vanhanen electrolyzer temperature model during the eight-day period but the two are not different in terms of predicting the hydrogen production. The Vanhanen model is much simpler than the Jacobson model, so we have chosen it as the preferred electrolyzer temperature model.

Data are recorded in three-minute time intervals at the SERC project. We used this time interval for much of the original work with the simulation. Weather files often use one-hour time intervals to report data. We were interested to see if the longer time interval would decrease the accuracy of the simulation. The results presented in Table 5.3 show that there is no significant difference in the prediction of hydrogen production between three-minute and one-hour time intervals. Trial runs with longer time intervals suggest that two- or four-hour intervals can be used without significant error.

A final run was done with the electrolyzer environmental air temperature set to a constant value of 20°C. This also did not result in a significant change in the predicted hydrogen production. This means that the user can set the electrolyzer environmental temperature to a constant value when reliable data for this temperature are not available.

Table 5.3: Hydrogen Production Comparisons

Model Configuration	Hydrogen Production (stand. liters)	Residual (Predicted – Measured)	Percent Error
Measured Value	53,550	n/a	n/a
Vanhanen, 1 h intervals, T_{amb} from Data[1]	55,400	1850	+3.5%
Vanhanen, 3 min intervals, T_{amb} from Data	55,350	1800	+3.4%
Vanhanen, 1 h intervals, T_{amb} = 20°C[2]	55,400	1850	+3.5%
Jacobson, 1 h intervals, T_{amb} from Data		1850	+3.5%
Jacobson, 3 min intervals, T_{amb} from Data	55,400	1850	+3.5%

[1] T_{amb} is the Electrolyzer Environmental Air Temperature; in this configuration the data were collected in the space that contains the electrolyzer.

[2] In this configuration the Electrolyzer Environmental Air Temperature was set equal to a constant 20°C.

7.2 PV Array Delivered Power Modeling

Perhaps the most interesting aspect of the modeling occurred when examining the power output of sub-array #1 and the power received by the electrolyzer. As demonstrated in Figure 5.5, the PV model very closely simulates the measured IV curve for this sub-array.

This is also the sub-array that is furthest from the electrolyzer, has the longest wire runs, and hence has the greatest resistive losses. When the system was designed, wire and cables were sized using the Table of Conductor Properties in the National Electric Code Handbook to limit voltage drop to 2%. Resistance measurements of the #2 AWG wire that runs from the sub-array to the junction block in the gas generation building revealed the actual value to be 24% higher than the values in the NEC table. Similar tests on the 4/0 cable running from the bus bar to the electrolyzer found a value that was 19% higher than the design value.

Plugging these values into the voltage loss to wire resistance portion of the model and including other resistive components such as the sub-array fuse disconnect, the blocking diode, and the relays, revealed that of a possible 656 peak Watts produced, nearly 60 W, or 9% of the total, were lost to these components.

To date we have not observed any increased voltage requirements for the electrolysis module as predicted by Teledyne. An analysis of electrolyzer data has shown that as the unit reaches operating temperature, only 22.5 V are required for electrolysis. This is 4 V below the maximum power point for this sub-array. This mismatch loss results in another 40 W loss for a total power loss from all sources of 15%. This is a substantial loss.

Possible remedies for these losses include the installation of larger wires, installation of higher capacity rated blocking diodes, or additional diodes could be paralleled to reduce power loss. Power loss from the sub-array disconnects is small in comparison to the other devices, but some reduction could be made by replacing one of the series fuses in each unit with a low resistance conductor. Finally, this analysis shows that substantial improvement in PV efficiency (and hydrogen production efficiency) can be made by adding two cells to the electrolyzer to enhance the electrolyzer-sub-array-voltage match.

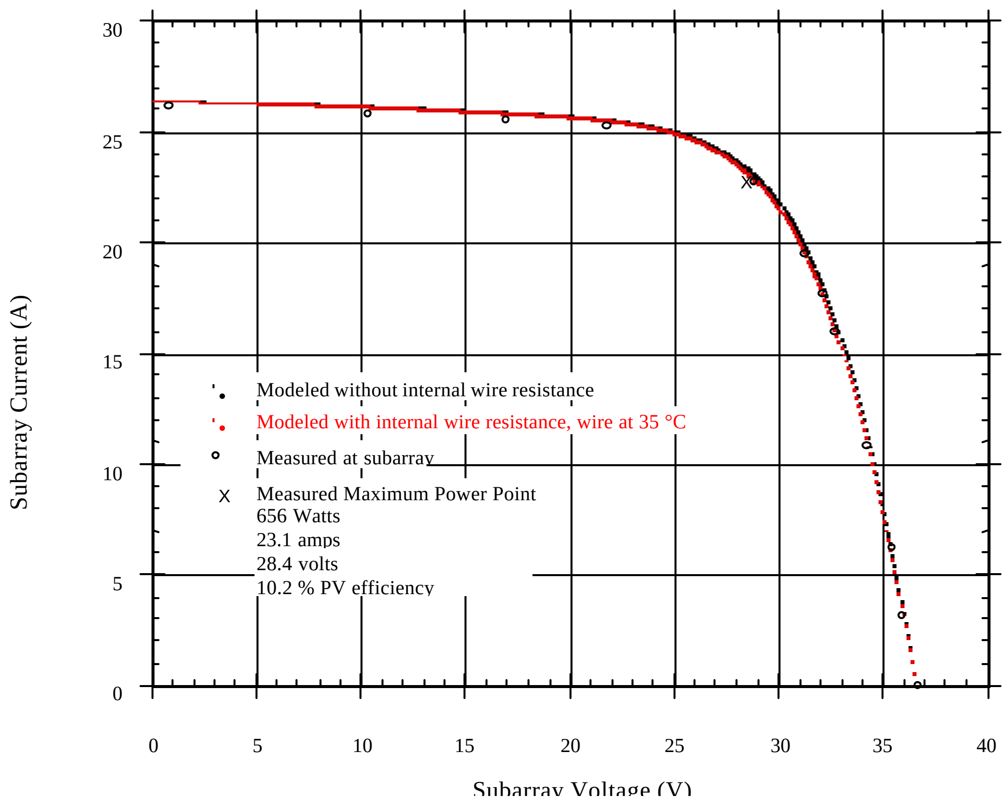

Figure 5.5: Subarray 1, predicted vs. measured IV curves

7.3 Future Modeling

These models are not limited to the specific components and configuration found in our system. By simply changing the input parameters, virtually any conceivable system can be modeled at any location for which solar data are available. We have used the National Renewable Energy Laboratory's Solar and Meteorological Surface Observation Network data to simulate similar systems in other parts of the country. Specifically, we are using these models in the design of the Palm Desert Solar Hydrogen Refueling Station, which is the subject of a separate report.

8. PUBLIC ACCEPTANCE AND SAFETY

The public has responded very well to this project. We have received very little negative feedback, and in general, people seem to be very taken with the idea of solar hydrogen as an energy source. We have not had any problems with inspectors or fire marshals. We attribute this to the fact that we have done substantial work addressing issues of safety and code compliance prior to construction. Through this, we were able to discuss the issues with the inspectors and to bring up specific safety issues ourselves that the inspectors had not considered.

8.1 Safety Interlocks

The various safety interlocks were enumerated earlier. In addition we also have mechanical excess flow valves on the hydrogen storage tanks. These isolate the tanks if a hydrogen gas line is damaged or disconnected.

8.2 Emergency Response Plan

During the spring and the summer of 1993, we developed an emergency response plan. This document includes general information about the hazards associated with hydrogen gas as well as an outline of procedures to follow in an emergency situation. It defines procedures for situations including hydrogen fires, chemical spills involving potassium hydroxide or hydrochloric acid, and earthquakes. In addition, it clearly describes a number of ways that the solar hydrogen system can be shut down in the event of an emergency.

While the emergency response plan was developed with our staff in mind, it also lays the groundwork for training the staff of the Telonicher Marine Lab. This lab lies adjacent to our facility and the air compressor used to aerate their fish tanks is powered by the solar hydrogen system. If the system is to operate in an unattended, continuous mode it is important to train members of the Marine Lab staff how to react in an emergency situation.

Thus while we are taking great pains to insure that our system is safe and reliable, we recognize that accidents can happen. With this plan, we are working to ensure that if an accident does occur, we will be able to respond quickly and efficiently to minimize the threat to human lives as well as potential damage to the system. Fortunately, no such accidents have occurred in our 8 years of operation.

8.3 Fault Tree Development and Testing

In order to develop and test the safety interlock system, we created a fault tree for our facility, and then tested those 'reasonable-to-perform' faults under actual operating conditions. For those fault tests that could not easily be simulated, such as an earthquake or a flood, we relied upon thought experiments and manufacturer's safety information to estimate the possible ramifications on the operation of the system and its equipment. When deficiencies were found, software and/or hardware modifications were made.

In order to cover the equipment that is in place, the fault tree is organized into three major sections: electrical, electrolyzer, and general. Each of these sections is built off a branched structure that lists the possible abnormal conditions with the affected components. A reader finds the possible fault conditions on the first branch, and then scans to the right for the equipment that might be affected with more specific faults conditions listed beneath each component.

The intended use of the fault tree is twofold. The first was to help Schatz personnel identify compromising or detrimental operating situations for the system, and then use this information to design the safety interlock system (and system control algorithms). The second purpose is to facilitate testing of the safety interlock system, both initially and in the future. Although the system contains many "off-the-shelf" components, the shared history of operation for these components in the setting of a solar hydrogen energy system is still very young. As a result, we intentionally made the fault tree general in nature, rather than attempting to specify every possible fault condition and component combination or interrelationship. In this way more variability is included so that the fault tree might better serve to uncover deficiencies in the safety interlock system.

8.4 Maintenance Schedule

To ensure safe and reliable operation of the system and related equipment, we developed a comprehensive maintenance schedule that includes regular weekly, monthly, biannual, and annual inspections. While most of the review intervals follow manufacturer's timetables, several have been made more frequent to ensure a margin of safety.

9. FUTURE PLANS

We intend to continue operating the Schatz Solar Hydrogen Project into the foreseeable future. When funding becomes available, we will construct a new fuel cell stack that incorporates the many design improvements that we have developed in our vehicle research. An improved fuel cell should increase the electrical storage efficiency by several percentage points.

10. CONCLUSIONS

We believe that the Schatz Solar Hydrogen Project has demonstrated that hydrogen is a viable medium for the storage of electrical energy derived from the sun. Over eight years of operation we have found the following efficiencies:

– Faraday	96.4%
– Electrolyzer	79.2%
– Voltage	84.0%
– Fuel cell	43.1%
– Overall electrical storage	34.0%

The use of solar hydrogen generation systems in regions that are rich in solar energy would enable the efficient long-term storage of this energy either for later use or for export to other locations.